NASA Technical Memorandum 88968

Spectrum-Modulating Fiber-Optic Sensors for Aircraft Control Systems

(NASA-TM-88968) SPECTRUM-MODULATING FIBER-OPTIC SENSORS FOR AIRCRAFT CONTROL SYSTEMS (NASA) 9 p CSCL 01D

N87-17700

Unclas

G3/07 43330

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Prepared for the
1st International Military and Government
Fiber-Optic and Communications Exposition
sponsored by the Fiber-Optic Communications Association
Washington, D.C., March 18–19, 1987

SPECTRUM-MODULATING FIBER-OPTIC SENSORS FOR AIRCRAFT CONTROL SYSTEMS

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E-3436

SUMMARY

This paper describes a family of fiber-optic sensors for aircraft-engine control systems. Each of these sensors uses a spectrum-modulation method to obtain an output which is largely independent of the fiber link's transmissivity. This report describes a position encoder, which uses a code plate to digitally modulate the sensor's output spectrum. Also described are pressure and temperature sensors, each of which uses a Fabry-Perot cavity to modulate the sensor's output spectrum as a continuous function of the measurand. A technique is described whereby a collection of these sensors may be effectively combined to perform a number of the measurements which are required by an aircraft-engine control system.

I. INTRODUCTION

Fiber-optic data transmission offers considerable advantages for aircraft-engine control systems. The most notable advantage of fiber-optic data links is their immunity to electromagnetic interference, yet they offer numerous other advantages such as high bandwidth, small size, and light weight. In order to obtain the maximum benefit from fiber optics, all the control system's data signals could be transmitted optically, including the sensor and actuator signals. Ideally, these optically linked sensors and actuators would be electrically passive, to minimize the number of locations to which electrical power must be distributed and also to permit these sensors and actuators to operate reliably at high temperatures. Considerable research has been performed to develop fiber-optic sensors and actuators which could be used in a fly-by-light engine control system.[1-9,12-15] An engine control system requires accurate measurements of a number of different physical parameters, principally temperatures, pressures, and flow rates as well as linear and angular positions, and rotation speeds. The considerable transmissivity variations that occur in practical fiber-optic links frequently makes it difficult to achieve the accuracy which is required for these measurements. This report describes a family of electrically-passive fiber-optic sensors, each member of which uses a spectrum-modulation method to obtain an output that is largely independent of the fiber-link's transmissivity.

II. INTRODUCTION TO SPECTRUM-MODULATING SENSORS

The development of spectrum-modulating sensors is prompted by the poor stability of the simplest type of fiber-optic sensor, the so-called intensity-modulating sensor. The intensity-modulating sensor has a transmissivity which is a monotonic function of the measurand. Optical fibers deliver light to the remotely-located sensor and return the light which the sensor transmits. The intensity of the light returned from the sensor is then measured in order to determine the measurand's value. The stability of this type of sensor is limited in practice by its sensitivity to variations in the fiber link's transmissivity. In practical fiber-optic links considerable transmissivity variations can be produced by any combination of the following factors: replacement or repair of the optical fibers and connectors, damage or contamination of connector surfaces, temperature effects, fiber bending, and nonrepeatable connector losses.

One way to obtain a high degree of link independence is to use a spectrum-modulating sensor in conjunction with a broadband source (usually one or possibly two light-emitting diodes or LED's). This type of sensor modulates light of different wavelengths as substantially different functions of the measurand. Because the fiber link's transmissivity is largely wavelength-insensitive (for sufficiently small wavelength differences) the spectrum of the light returned from the sensor can be analyzed to obtain a link-independent estimate of the measurand's value.

A simple experiment was performed to demonstrate the effectiveness of a spectrum-modulating method of loss-compensation. An LED with an 835-nm peak wavelength and a half-power spectral width of 50 nm is the optical source. The optical fiber has a 100-μm core diameter and a 0.3 numerical aperture (N.A.). The fiber-optic link consists of four 10-m long fibers which are joined together by connectors. The light exiting the fiber link is collimated by a lens and then divided by a beam splitter. Each of the splitter's output beams is directed through a bandpass filter (BPF1 or BPF2) and onto a photodiode (PD1 or PD2, respectively). The bandpass filters BPF1 and BPF2 have peak wavelengths of 830 and 840 nm, respectively, and both filters have half-power bandwidths of 10 nm. The outputs of PD1 and PD2, I_1 and I_2, respectively, are measured and the results ratioed to obtain the compensated signal $Y = I_1/I_2$.

The sensitivity of Y to various disturbances of the fiber link was measured in order to evaluate the stability of a sensor whose output is the ratio of its transmissivities at two different wavelengths (830 and 840 nm in this instance). First, the compensated signal Y was measured after each of 20 break/remake cycles of one of the fiber link's connectors. The relative standard deviations of I_1 and Y were 13 and 0.1 percent, respectively. In another experiment, prior to each of 20 Y measurements, two of the link's fibers were alternately removed or replaced. The additional fibers reduced the link's transmissivity by an average of 3.7 dB, yet each of the 20 Y measurements fell within ±0.5 percent of the mean value. The variations in I_1 observed during both these experiments show the difficulty in obtaining a high degree of accuracy using a simple intensity-modulating transducer (unless the installed sensor is frequently recalibrated, an impractical procedure for an aircraft control system). The stability of the compensated signal Y, on the other hand, shows that well-designed spectrum-modulating sensors may be used to obtain high accuracies without requiring extraordinary installation and maintenance procedures.

III. DIGITAL POSITION ENCODERS

A particularly effective spectrum-modulation method is a digital technique where a binary representation of the measurand's value is encoded into the sensor's output spectrum by way of the presence or absence of light at a number of adjacent wavelength channels.[8,9] The resolution of this type of transducer is 2^N, where N is the number of binary channels or bits. Reflective or transmissive binary code plates are commonly used to encode a linear or angular position via N on/off optical signals. In commercial position encoders these optical signals are generated and detected within the transducer. A fly-by-light control system requires electrically passive versions of these devices, where an input and an output optical fiber provide the only link to the transducer. One way to combine N optical signals so that they may be transmitted through a single output fiber (and then separated once again at the receiver) is to use wavelength-division multiplexing or WDM.

Figure 1 shows, schematically, a digital linear-position transducer which uses a micro-optic wavelength multiplexer or MUX. Broadband light from an LED is transmitted to the encoder by the transducer input fiber. Within the transducer, the incoming light travels through a fused-fiber coupler and a MUX input/output fiber to a grating/lens assembly.[10,11] The grating/lens assembly uses a 5-mm diameter graded-index rod lens (GRIN lens) to direct a collimated beam onto the grating. The reflective grating angularly disperses the incident beam, and the lens focuses each reflected wavelength onto a different portion of the code plate's read aperture. Consequently, a different wavelength of light interrogates each channel of the reflective code plate. The difference in the wavelengths which are directed to adjacent channels is given by $\Delta\lambda = d\lambda/dX \cdot \Delta X$, where $d\lambda/dX$ is the grating/lens assembly's linear dispersion and ΔX is the center-to-center spacing of the code plate's channels. The code plate's position, relative to the read aperture, determines whether a channel is in a logic one or zero state. If the channel is in the logic-zero state the incident light is absorbed, but if the channel is in the logic-one state, the incident light is reflected. The wavelengths reflected by the code plate retrace their paths through the grating/lens assembly and the MUX input/output fiber to the fiber coupler. The fiber coupler then directs the encoder's output through the transducer output fiber to the receiver.

The receiver separates or demultiplexes the wavelength channels using a grating/lens assembly which is identical to that used by the encoder. The receiver's grating/lens assembly disperses the encoder's output spectrum across the elements of a linear photodiode array. The array's elements have a center-to-center spacing equal to that of the code plate's channels, and the array is positioned on the face of the GRIN lens so that each photodiode receives the light from one encoder channel. Each photodiode's output is amplified and the result is compared with a reference voltage to determine whether the corresponding encoder channel is a logic one or zero. The reference voltage may be derived from the signal of a photodiode which detects the output of a reference channel, which is always a logic-one, so that the reference level will track the changes in the fiber-link's transmissivity, thereby permitting the transducer to operate reliably over a wide range of signal levels.

To demonstrate the feasibility of this type of transducer a breadboard 10-bit encoder was constructed using an 1800 line per mm grating.[8] A simulated code plate (having only one state) was constructed by ruling a first surface mirror with a phonograph stylus. The channel width was made equal to the fiber's core diameter, 100 μm, and the channel spacing was made equal to the fiber's cladding diameter, 140 μm, giving a guard band between each channel of width 40 μm. The grating/lens assembly has a spectral dispersion of 74 nm/mm. Consequently, the wavelength difference between channels is 10 nm, and the total wavelength difference between the first and tenth channels is 90 nm. To obtain a sufficiently broad spectrum of light with which to interrogate all ten channels, the outputs of two LED's with offset but overlapping spectra are combined, using a beam-splitter, and then injected into the transducer input fiber. LED's with peak wavelengths of 820 and 860 nm are used. The spectral nonuniformity of the dual-LED source causes a 5-dB variation among the signals incident on the code-plate channels. The resulting channel-to-channel variations in the detected signals can be equalized by adjusting the preamplifier gains.

The breadboard encoder's output spectrum was analyzed using a scanning monochromator, and the results are shown in Fig. 2. The observed on/off contrast ratio is 10 dB. The optical loss from the MUX input/output fiber to the reflective code plate and back to the input/output fiber was separately determined to be 12 dB. After accounting for the two-way loss of the fiber coupler (approximately 8 dB), the transducer's insertion loss is estimated to be 20 dB.

Another multiplexing technique for electrically passive optical position encoders, time-division multiplexing (TDM), has been the subject of considerably more development effort than has the WDM technique described here.[12] Yet the wavelength-multiplexed encoder offers some significant advantages. In the time-multiplexed device, short optical pulses are delivered to the transducer which uses fiber couplers and fiber delay lines to time multiplex the code plate's binary signals as a series of output pulses. One disadvantage of this time-multiplexed encoder is its larger size and greater weight than the wavelength-multiplexed encoder; the time-multiplexing delay-line spool may contain a total of 200 m of fiber and is therefore quite bulky as well as being somewhat environmentally sensitive. Another disadvantage of the time-multiplexed encoder is the high bandwidth which is required to detect the approximately 10 ns wide optical pulses. The bandwidth requirements of the wavelength-multiplexed encoder, on the other hand, are minimal. Therefore, for a given level of optical power, the time-multiplexed encoder is subject to a considerably greater noise level. A potentially more significant advantage of the wavelength-multiplexed digital encoder arises due to the usefulness of the spectrum-modulation method for providing link-independent analog-type temperature and pressure measurements. Thus, a fly-by-light engine control system may derive a considerable advantage by making extensive use of both digital and analog spectrum-modulating sensors, so that all of the control system's temperature, pressure, and position sensors may share the same spectrum-analyzing receiver. A system of spectrum-modulating sensors will be described in Section V of this report, following a discussion of temperature and pressure sensors in the next section.

IV. ANALOG TEMPERATURE AND PRESSURE SENSORS

The temperature and pressure sensors considered here use a reflective Fabry-Perot cavity to modulate broadband light from an LED. As a function of wavenumber k, where $k = 2\pi/\lambda$, the sensing cavity's reflectance is a minimum at each of the cavity's resonant wavenumbers, i.e., at $k = N\pi/nL$, where N is an integer, n is the cavity's refractive index and L is the distance between the cavity's reflective surfaces. By causing the product nL to vary as a function of the measurand, the sensor encodes the measurand's value via the locations of its spectral-reflectance minima. The sensor's design ensures that the product nL is sufficiently large that the LED's spectrum always contains at least one of the sensing cavity's resonant wavenumbers. The measurand's value can then be determined by analyzing the sensor's output spectrum, provided the spectrometer used has sufficient resolution to discern the spectral features of the sensor's output. The micro-optic spectrometer which was used in the encoder's receiver is well-suited for this application. To analyze the output of an analog-type Fabry-Perot sensor, the receiver electronics must be modified so that the analog outputs of the photodiodes are digitized and the results transmitted to a microprocessor. The processor must then use an algorithm to operate on these results in order to obtain an estimate of the measurand's value.

A spectrum-modulating pressure sensor can be constructed by using a diaphragm to displace one of the cavity's mirrors.[13,14] A temperature sensor can be constructed by using an etalon whose mirror separation is controlled by a thermally-expansive element,[3] or by using a solid etalon whose refractive index is a sensitive function of temperature.[15] This latter type of temperature sensor will be discussed in detail in order to illustrate the general principles of these Fabry-Perot sensors.

A spectrum-modulating temperature sensor was constructed using a thick-film Silicon Carbide (SiC) etalon.[15] The resonant wavenumbers of this solid Fabry-Perot cavity are modulated as a function of temperature due, primarily, to the temperature-dependence of SiC's refractive index. Light from an LED travels through an input fiber to a coupler, which directs the light through a short length of high-temperature fiber to the etalon. The light reflected by the etalon travels back through the coupler which directs the reflected light through an output fiber to a spectrometer. The temperature-sensing probe is shown schematically in Fig. 3. The sensing etalon is a single crystal of SiC which has a thickness of about 10 μm. A ceramic cement is used to attach the SiC crystal to the end of the high-temperature fiber. To protect the SiC crystal a piece of Si wafer is affixed to the crystal's exterior surface using a glass frit. The refractive-index discontinuities at the crystal's front and back surfaces yield reflectivities of 20 and 8 percent, respectively.

A scanning monochromator was used to determine the effect of temperature on the sensor's output spectrum. The topmost trace of Fig. 4 shows the LED's spectrum. The next two traces show the sensor's output spectra that were obtained at temperatures of 20 and 250 °C (the vertical scale for both these traces is identical). The positive coefficient of dn/dT causes the spectral peaks to shift to longer wavelengths with increasing temperature. The bottom two traces, designated A and B, show the spectral transmissivities of two adjacent channels of the micro-optic spectrometer, where the fiber core diameter is 100 μm, the channel separation is 140 μm, and the grating's line density is 2400/mm. These results show that this miniature spectrometer has sufficient resolution to discern the essential features of the sensor's output spectrum.

In the sensor which was used to obtain the results of Fig. 4, the SiC crystal's surface defects significantly reduced the degree to which the reflected spectrum was modulated. If the modulation index is defined as $(R_{MAX}-R_{MIN})/R_{MAX}$, where R_{MAX} and R_{MIN} are the etalon's maximum and minimum reflectivities, then the modulation index obtained in Fig. 4 is 0.25. Somewhat more carefully selected SiC crystals have routinely yielded a modulation index of 0.5. This figure is probably adequate, but further improvements in the modulation index could be obtained, if desired, by polishing the crystal's surface, rather than using the crystals as-grown.

The results of Fig. 4 show that a two-channel spectrometer, with spectral passbands A and B, could be used to determine the sensor's temperature. If the sensed temperature were increased, then the output of channel A would increase while the output of channel B would decrease. Therefore the ratio of these two outputs could be used to determine the sensed temperature independently of the fiber link's transmissivity. The extreme values of this particular sensor's range are approximately those temperatures at which the data of Fig. 4 were taken. Beyond these temperatures, the sensitivities of both output channels go to zero. A greater modulation index than was obtained in Fig. 4 is clearly desirable, yet these preliminary results demonstrate the general principle.

Although a two-channel spectrometer can provide immunity from the effects of wavelength-independent variations in the fiber transmissivity, a spectrometer with a larger number of channels may provide greater accuracy because of the additional information which is obtained. This additional information might be used to compensate the effects of temperature-induced shifts of the LED's output spectrum. The effects of wavelength-dependent variations in the fiber-link's transmissivity might be compensated as well by a somewhat more sophisticated algorithm.

V. A SYSTEM OF SPECTRUM-MODULATING SENSORS

It has been shown that an aircraft-engine control system's temperature, pressure, and position measurements can be performed by a family of spectrum-modulating sensors, each of which uses the same type of micro-optic spectrometer. Despite the small size of this device (approximately 5 by 5 by 20 mm), it is impractical to use a separate spectrometer for each sensor. Figure 5 shows a technique whereby all the control system's sensors may share the same spectrometer, via a time-multiplexing technique. Each sensor is interrogated by a separate LED, which operates under the control of a microprocessor. Each sensor's output is transmitted to one fiber of a linear fiber array which delivers the sensor outputs to a grating/lens assembly. The fiber array is aligned parallel to the grating's grooves, so that the grating/lens assembly disperses the sensors' output spectra across the elements of the photodiode array. The microprocessor sequentially operates the LED's so that the photodiode array detects, in sequence, each sensor's output spectrum. As each sensor is interrogated, the photodiode outputs are digitized and then transmitted to the microprocessor. The processor uses an algorithm appropriate to that particular sensor to obtain the measurand's value, before it switches the LED's to interrogate the next sensor in the sequence.

VI. CONCLUSION

A family of fiber optic sensors has been described which may be used to perform the temperature, pressure, and position measurements which are required by an aircraft-engine control system. These sensors use a spectrum-modulation method to obtain a high degree of immunity from the effects of fiber-transmissivity variations. A technique has been described whereby all these sensors may share the same receiver, thus minimizing the amount of space within the engine control unit which must be devoted to sensing functions.

ACKNOWLEDGMENT

K. Fritsch wishes to acknowledge support of this work by NASA Lewis Research Center grant NAG3-571.

REFERENCES

1. Pitt, G.D., et al.: Optical-fibre Sensors. IEE Proc.: Part J. Optoelectron., vol. 132, no. 4, Aug. 1985, pp. 214-248.

2. Mossey, P.W.: 1700 °C Optical Temperature Sensor. (R86AEB267, General Electric; NASA Contract NAS3-24085) NASA CR-175108, 1986.

3. Quick, W.H.; James, K.A.; and Coker, J.E.: Fiber Optics Sensing Techniques. Optical Fibre Sensors, IEE Conference Publication No. 221, 1983, pp. 6-9.

4. Snitzer, E.; Morey, W.W.; and Glenn, W.H.: Fiber Optic Rare Earth Temperature Sensors. Optical Fibre Sensors, IEE Conference Publication No. 221, 1983, pp. 79-82.

5. Berak, J.M.; Grantham, D.H.; and Eder, M.: Optical Switching of High-Temperature GaAs Devices for Digital Control of Aircraft Direct-Drive Actuators. (UTRC-R86-926733-27, United Technologies Research Center; NASA Contract NAS3-24219) NASA CR-179465, 1986.

6. Gurney, J.O., Jr.: Photofluidic Interface. J. Dynamic Systems, Measurement, and Control, vol. 106, no. 1, Mar. 1984, pp. 90-97.

7. Collier, S.J.; McGlade, S.M.; and Stephens, P.E.: The Optical Actuation of a Process Control Valve. Optical Fibre Sensors, IEE Conference Publication No. 221, 1983, pp. 57-61.

8. Fritsch, K.; and Beheim, G.: Wavelength-Division Multiplexed Digital Optical Position Transducer. Opt. Lett., vol. 11, no. 1, Jan. 1986, pp. 1-3.

9. Dakin, J.P.; and Liddicoat, T.J.: A Wavelength Multiplexed Optical Shaft Encoder. Measurement and Control, vol. 15, no. 5, May 1982, pp. 176-177.

10. Erdmann, R.; Perry, C.H.; and Parmenter, C.: Prism Gratings for Fiber Optic Multiplexing. Fibre Optics Multiplexing and Modulation, E.J. Miskovic, ed., SPIE-417, SPIE, 1983, pp. 12-17.

11. Kobasyashi, K.; and Seki, M.: Micro-Optic Grating Multiplexers and Optical Isolators for Fiber Optic Communications. IEEE J. Quantum Electron, vol. QE-16, no. 1, Jan. 1980, pp. 11-22.

12. Stanton, R.O.: Digital Optical Transducers for Helicopter Flight Control Systems. Fiber Optic and Laser Sensors, E.L. Moore and O.G. Ramer, eds., SPIE-412, SPIE, 1983, pp. 122-129.

13. Beheim, G.; Fritsch, K.; and Poorman, R.: Fiber-Linked Interferometric Pressure Sensor. Submitted to Rev. Sci. Instrum., 1987.

14. Belsley, K.L.; Huber, D.R.; and Goodman, J.: All-Passive Fiber-Optic Pressure Sensor. InTech Vol., vol. 33, no. 12, Dec. 1986, pp. 39-44.

15. Beheim, G.: Fibre-Optic Thermometer Using Semiconductor-Etalon Sensor. Electron. Lett., vol. 22, no. 5, Feb. 27, 1986, pp. 238-239.

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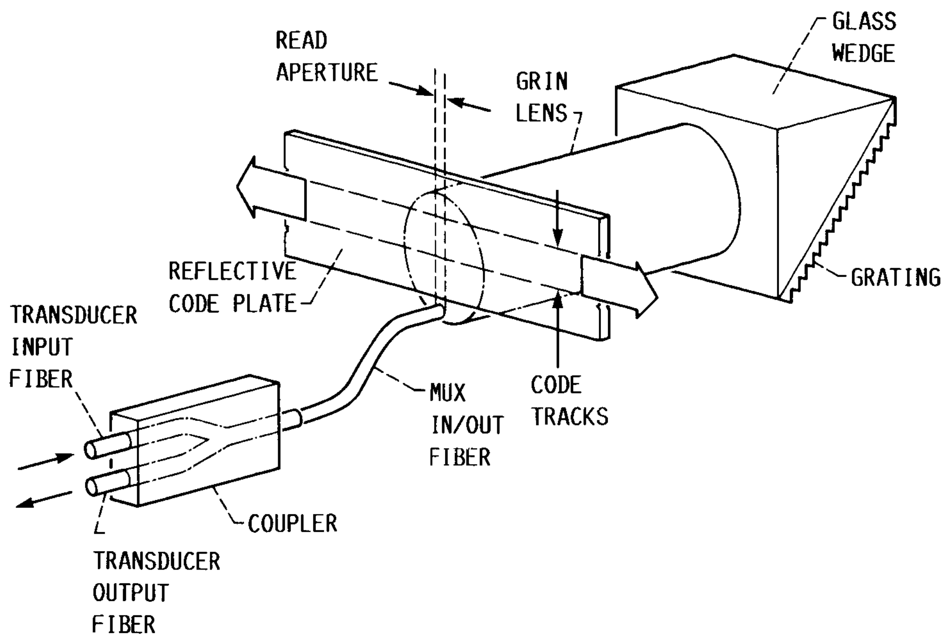

FIGURE 1. - WAVELENGTH-DIVISION MULTIPLEXED LINEAR-POSITION ENCODER.

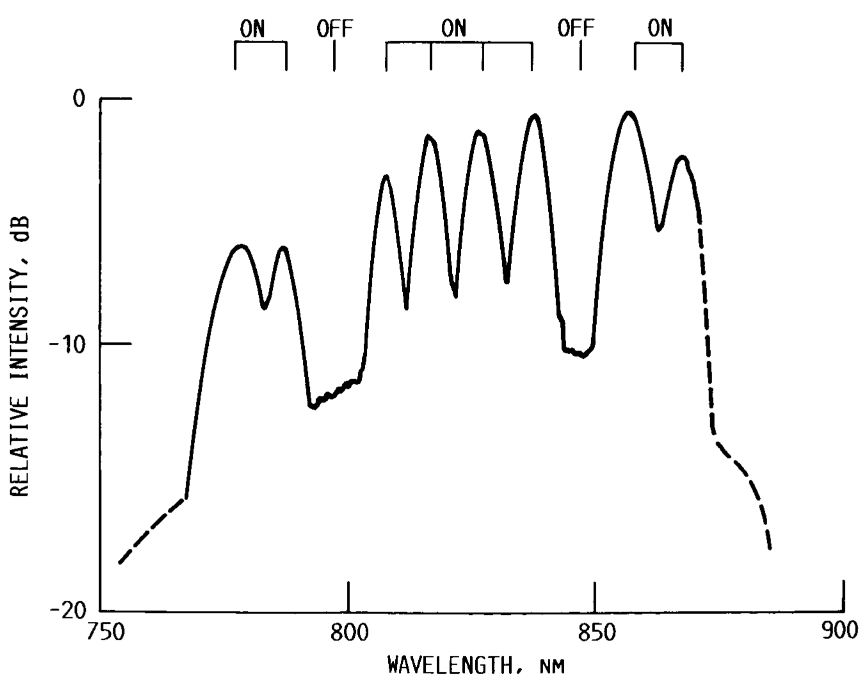

FIGURE 2. - OUTPUT SPECTRUM OF WAVELENGTH-MULTIPLEXED ENCODER.

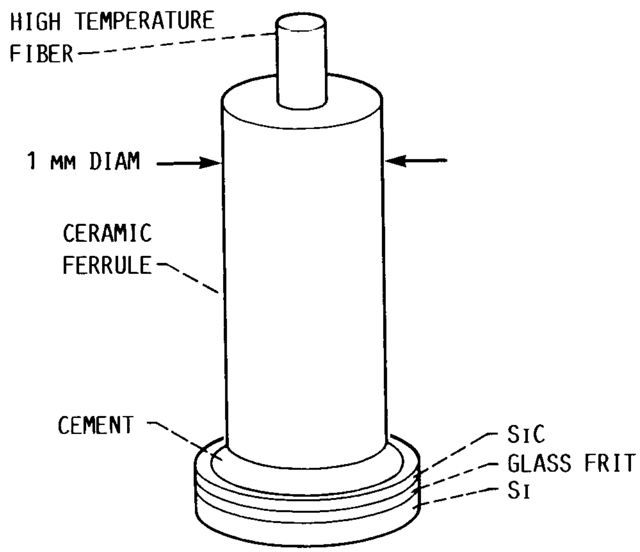

FIGURE 3. - SPECTRUM-MODULATING TEMPERATURE SENSOR WHICH USES A SIC ETALON.

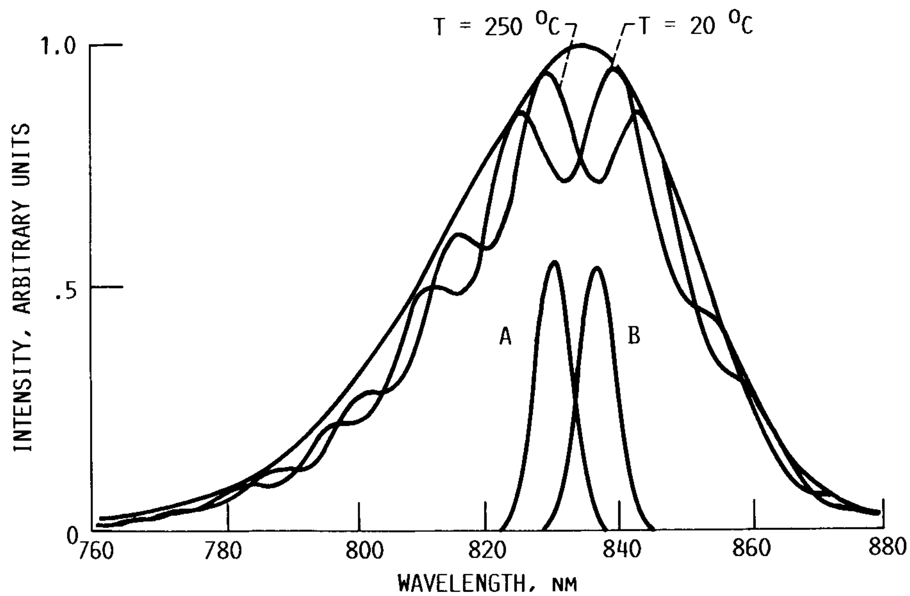

FIGURE 4. - OPTICAL SPECTRA, FROM TOP TO BOTTOM: LED SPECTRUM; OUTPUT SPECTRA OF SENSOR AT TEMPERATURES OF 20 °C AND 250 °C; SPECTRAL TRANSMISSIVITIES OF TWO ADJACENT SPECTROMETER CHANNELS, A AND B.

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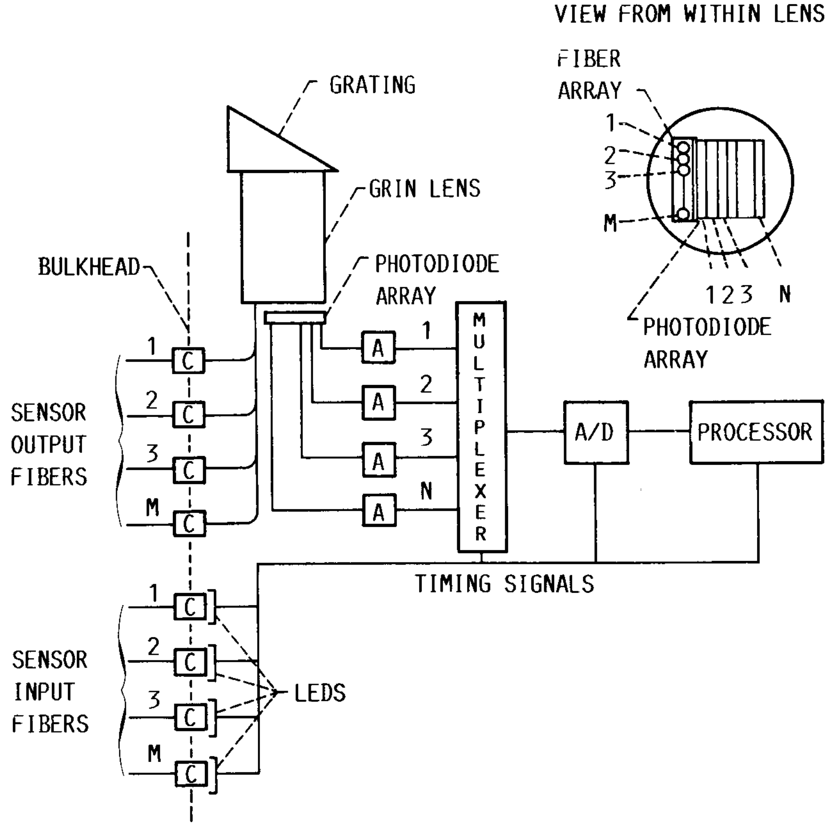

FIGURE 5. - A SYSTEM OF M SPECTRUM-MODULATING SENSORS WHICH USES A TIME-MULTIPLEXED N-CHANNEL SPECTROMETER. HERE THE PREAMPLIFIERS ARE DESIGNATED A, THE BULKHEAD CONNECTORS ARE DESIGNATED C, AND THE ANALOG-TO-DIGITAL CONVERTER IS DESIGNATED A/D.

1. Report No. NASA TM-88968	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Spectrum-Modulating Fiber-Optic Sensors for Aircraft Control Systems		5. Report Date
		6. Performing Organization Code
7. Author(s) Glenn Beheim and Klaus Fritsch		8. Performing Organization Report No. E-3436
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for 1st International Military and Government Fiber-Optic and Communications Exposition sponsored by the Fiber-Optic Communications Association, Washington, D.C., March 18-19, 1987. Glenn Beheim, NASA Lewis Research Center; Klaus Fritsch, Department of Physics, John Carroll University, Cleveland, Ohio 44118.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fiber-optic sensors; Temperature sensors; Position encoders; Pressure sensors	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161